Intent to Develop Alberta offset system Quantification Protocol: *Quantification Protocol for Biological Methane Oxidation*

Please contact Climate Change Central with any questions or clarification of requirements at contact@climatechangecentral.com.

This Intent to Develop an Alberta offset system Quantification Protocol document is intended to provide Alberta Environment with an overview of the proposed protocol idea to demonstrate how this protocol will meet the requirements of the Alberta offset system. The protocol developer is required to present this information to Alberta Environment and must receive approval in concept for the protocol before the protocol idea will be considered for development in the Alberta offset system.

Familiarity with and general knowledge of the Alberta offset system is required prior to initiating a protocol. Information on the Alberta offset system is available on the Carbon Offset Solution website (http://carbonoffsetsolutions.climatechangecentral.com) and on the Alberta Environment website (http://environment.alberta.ca/02275.html).

Alberta Environment will review the submitted information in order to assess and provide feedback on the following elements:

- How the proposed protocol meets the eligibility criteria in Section 7 of the Specified Gas Emitters Regulation;
- Applicability of the proposed protocol against purpose and intent of the Alberta Offset System;
- Baseline adoption levels and credit potential for Alberta;
- Baseline, project condition, and key assumptions for the proposed protocol;
- Key stakeholders and technical experts in the field; and
- Relevant science and technical information

General Description of the Proposed Protocol[1] **[Provide a written overview on the intent, purpose and relevant background information on the protocol.]**

Solid waste landfills contribute significant volumes of methane emissions to the atmosphere. It is anticipated that in Canada, these landfills alone are responsible for up to 26% of the anthropogenic methane emissions. The national inventory estimates that there were 22 Mt of total emissions from the waste sector in 2008, of which municipal solid waste (MSW) landfills and wood waste landfills, accounted for 20 Mt. Methane emissions produced by the decomposition of biomass in MSW landfills were responsible for 83% of the emissions from this Sector (Environment Canada, 2010).

Methods used to control landfill gas include the installation of an impervious cover on closure. This cover is intended to reduce the infiltration of water from precipitation, which is known to increase and accelerate gas

[1] **Some important notes to consider:**

- *Protocols should be based on best available science.*
- *Follow the ISO 14064:2 standard processes – specifically addressing principles of conservativeness, completeness, relevant, consistent with others, accuracy and be completely transparent in development and descriptive processes.*
- *Be very clear with respect to the Measurement, Monitoring and Verification requirements to allow little interpretation.*

production inside the landfill. However, surface emissions will occur through a cover and may increase over time as a cover can deteriorate over time. There are many inactive landfills in Alberta many of which were not closed to the current standards for landfill covers. Several of these present potential environmental hazards and contribute to methane emissions to the atmosphere.

A common method for collecting landfill gas involves the intrusive installation of an active gas collection system to collect and destroy methane by combustion. These systems are feasible where the gas generation volumes are sufficient to justify the high capital and operating cost. Also, fugitive emissions through the cover can still occur even at sites with these systems are installed. Active gas extraction systems are difficult to justify at small and old landfills which together contribute a significant portion of landfill gas emissions. The national inventory indicates that methane emissions from MSW landfills increased by 18% between 1990 and 2008, despite an increase in landfill gas capture and combustion of 71% over the same period (Environment Canada, 2010).

A cost effective method that can be used to control fugitive emissions from landfill covers is the use of biological treatment in the form of microbial oxidation of methane otherwise known as biofiltration. This can be carried out in biofilter systems or within the cover layer, in biocovers. Biofiltration is a process in which waste gases are treated by passing a contaminated (methane containing) gas stream through a bed of porous solid medium enriched with microorganisms. These microorganisms biologically break down the pollutants into less harmful gases through an oxidation process using oxygen as a reducing agent. The microorganisms that can oxidize methane gas to produce carbon dioxide and water are referred to as methanotrophs. These methanotrophs are naturally occurring but in low quantities in many organic materials. Given sufficient oxygen availability, high concentrations of methane, and appropriate conditions methanotrophs can thrive. The function of a bio-filter or a biocap is to provide the environmental conditions to support a healthy and vigorous population of methanotrophs for effective oxidation. Bed materials used in typical bio-filters are soil, compost, wood chips or mixtures of these materials depending on what is available locally.

Biofiltration is a well-known and cost-effective technology which has been applied to removing environmental pollutants from contaminated gas steams for several decades (Yang and Minuth, 2002). It has been successfully used to eliminate or to treat air streams contaminated with various gases such as BTEX (Tahraoui and Denis, 1998), ethanol vapor (Arulneyam and Swaminathan, 2000), hydrogen sulfide and ammonia (Chung et al., 2001). However, the application of biofiltration in the treatment of methane is relatively new. In Alberta, there are several years of research on the oxidation of methane in landfills carried out by industry, academic and other institutions including Alberta Innovates, University of Calgary, University of Alberta, Edmonton Waste Management Centre of Excellence, and EBA, A Tetra tech Company (EBA). Much of this has been supported by research funds through organizations such as the Natural Science and Engineering Research Council of Canada (NSERC). This research has produced large amounts of data which can be found in a number of reports, Masters Theses (Philopoulos, 2006) (Perera, 2000) (Stein, 2000) (Wilhusen, 2002) and Ph.D. Theses (Pokhrel, 2006) (Hurtado, 2009). The research has thereby produced skilled individuals with the knowledge to carry out successful biofiltration installations in Alberta and beyond.

Despite the years of research, there is yet to be widespread adoption of the biofiltration of methane for landfill applications in Alberta. Much of the research carried out to date has been in laboratory scale. However, the technology has also been demonstrated to be successful in full scale pilot studies at the Leduc and District Regional Landfill. Alberta researchers have also been involved in biocover installations in Nanaimo, the Columbia-Shuswap Regional District of British Columbia, and in a full scale biofilter installation in a landfill in Fernie, B.C. These full scale installations have demonstrated this technology's effectiveness, and repeatability in varying material, environmental, and climatic conditions in locations other than Alberta. One of the drivers for these installations in British Columbia was a regulatory that lowered greenhouse gas reporting threshold requirements.

Intent **[Describe the protocol activity and reduction opportunity.]**

This protocol will apply to the oxidation of methane from landfills using biofilters and/or biocovers. Methane oxidation occurs naturally in soils and other porous media in the presence of oxygen. The microbial process involves the oxidation of methane through methanol to formaldehyde, which they then either assimilate for the synthesis of cell material, or further oxidize to carbon dioxide. The products of this process are carbon dioxide, water and biomass. As such, methane oxidation provides a greenhouse gas reduction since the global warming potential (GWP) of methane is 21 times that of carbon dioxide according to Intergovernmental Panel on Climate Change (IPPC, 2001). This protocol will serve as a tool for project proponents to follow in order to meet the measurement, monitoring, and greenhouse gas quantification requirements for reductions resulting from conversion of methane using the biofiltration process.

Baseline **[Explain the project baseline condition, adoption levels for the province, business as usual activity, general baseline assumptions, credit potential in Alberta, other relevant information.]**

The project baseline condition is the uncontrolled emission of methane to the atmosphere from landfilled waste. The method of quantifying the baseline condition is defined as the amount of methane oxidized that would otherwise have been released to the atmosphere, less the volume of methane that would have been required to have been captured under the applicable regulations. The baseline scenario for this protocol is dynamic as the volume and concentration of methane would be expected to change temporally and spatially, and the baseline condition may vary from project to project.

The current adoption level in the province is low due to the cost sensitivity of waste facilities. However, there is interest in biofiltration technology as demonstrated by the large volume of research and the active installations used as research facilities and demonstration projects.

Credit potential in Alberta is quite high. Suitable candidates include woodwaste landfills, small active municipal landfills, inactive and larger landfills with one or more cells that have closed and covered cells. In most cases active landfill gas extraction is not technologically or economically feasible. There are hundreds of these potential sites in Alberta and as many smaller and intermediate sized landfills are becoming more aware of the increasing credit potential, and lowering reporting and "paying in" thresholds, this protocol will provide them with a cost effective option to consider.

Project Condition **[Explain the project condition, activity creating the emission reduction or removal, other relevant information. Please include sample calculations if available. If unavailable, effort should be made to provide a high level technical assessment to of the reduction opportunity being claimed.]**

The technology was developed from laboratory research and data used to develop the protocol is from data from pilot scale biofiltration systems constructed and operated at the Leduc and District Regional landfill. The project has been underway since 2002. The methods used to develop the protocol include measurement and monitoring with readily available and cost effective equipment. Though methods can vary, there are four (4) elements to the development of a biofiltration project as follows:

- Determination of a suitable biofilter medium and its methane oxidation potential
- Determination of surface flux of the biofilter or biocap
- Determination of the influx of methane to the biofilter or biocap
- Determination of the methane removed

The method for this proposed protocol was developed from several years of research and innovation and has been developed by EBA in conjunction with Alberta Innovates.

Methane Oxidation Potential

The methane oxidation potential (MOP) is a measure of the ability of a given material to support methanotrophs and oxidize methane. The MOP of various materials is dependent on factors such as porosity, stability and moisture retention and source (material that has been previously exposed to methane has been found to have a higher initial mass of methanotrophs) (Hurtado, 2009). The methane oxidation potential can be determined in the laboratory using column experiments. This method involves the construction of a column of filter bed material where air is allowed enter passively (simulating a landfill cover). Methane is then passed through the column from the bottom, leaving through the top. The gas in the column is sampled at numerous depths to produce a profile of the oxidation of methane as it passes through the column. The flow of methane and the conditions within the column such as temperature and moisture content can be varied to determine the most appropriate conditions and performance under various gas flowrates. There is extensive research on the impact of moisture and temperature on performance of biofilters as well as supporting evidence from full scale pilot studies (Zeiss, 2002).

Surface Flux Measurements

Surface flux measurements are used to quantify the amount of methane gas leaving the biofilter or biocap. Flux is defined as the amount that flows through a unit area per unit time. A number of flux measurements are taken across the surface using a flux chamber and is the key to quantifying the amount of methane leaving the biofilter or biocap and in turn the amount of methane oxidized. There are variations on the design of flux chambers but the principal of operation is essentially the same. The flux chamber used for this protocol is a closed chamber which estimates flux by measuring the change in concentration of gas inside the chamber with respect to time. The chamber is placed on the surface and sealed to prevent air intrusion. Methane leaving the biofilter/biocover is allowed to build up within the chamber. The methane concentration within the chamber increases linearly within a short period of time. This time period is dependent on the flux and is determined empirically. The surface flux (m^3/ m^2 s) is calculated from the slope during this linear period.

The technique to determine the surface flux from the chamber was developed at the University of Calgary (Perera, 2000). The relationship between the flux and methane concentration is shown in the equation below.

$$J = \frac{dC}{dt} \times \frac{V_{fc}}{A_{fc}} \qquad (1)$$

Where, V_{fc} is the volume of the flux chamber (m^3), A_{fc} is the cross-sectional area of the flux chamber (m^2), and dC/dt is the rates of change in the percentage of gas i in the flux chamber (m^3 m^{-3} s^{-1}). The slope of the line, dC/dt, is determined by linear regression between methane concentration and elapsed time.

Methane Oxidization Quantification

The determination of the methane oxidation efficiency is conceptually simple. The difference between methane influx (amount entering the biofilter/biocover) and surface flux (amount leaving the system). However, the field measurement of the influx into the bottom of a cover or biofilter bed is not easily determined. The influx can vary both temporally and spatially. It is impacted by the rate of biodegradation taking place in the landfill but also by changes in barometric pressure and temperature which impacts diffusion or advection through the cover. The climatic conditions in Alberta are known to fluctuate significantly due to seasonal changes and Chinooks which has an impact biofilter/biocover application.

For most landfill biofiltration applications, the rate of influx of methane is unknown and needs to be determined. There are variations on determining the influx when it cannot be measured directly however all of these methods are based on a mass balance of methane and carbon dioxide entering and leaving the biofilter/biocover. For this protocol, the methane influx is determined by assuming that the total influx of landfill gas is equal to the landfill gas flux leaving the surface since every unit of methane that is oxidized produces and equal volume of carbon dioxide. The following equation is used to determine the methane influx (Zeiss, 2002).

$$Jin_{CH4} = Cin_{CH4} \times \left[Jout_{CH4} + Jout_{CO2} \right] \qquad (2)$$

Where, Jin_{CH4} is the methane influx (m^3/m^2d), $Jout_{CH4}$ and $Jout_{CO2}$ are the respective surface methane and carbon dioxide fluxes (m^3/m^2d), and Cin_{CH4} is the inlet concentration of methane. Since, in practice, the stoichiometric coefficients for carbon dioxide production have been found to be in the range of 0.2 to 0.9, the above equation may underestimate the methane influent flux (Zeiss, 2002).

The methane removal rate can then be determined by the following equation (Zeiss, 2002).

$$CH_4\ \mathrm{Re}moved = \frac{Jin_{CH4} - Jout_{CH4}}{Jin_{CH4}} \times 100 \qquad (3)$$

Relevant project emissions **[state which greenhouse gases will be affected by this project; direct and indirect emissions including positive and negative affects]**

The greenhouse gases directly affected by this project are methane and carbon dioxide. Through the implementation of this protocol, developers will reduce methane emissions through the oxidation of methane to carbon dioxide and water. This project will result in reduced emissions of methane to the atmosphere.

Specified Gas	Formula	100-year GWP	Applicable to Project
Carbon Dioxide	CO_2	1	Y
Methane	CH_4	21	Y
Nitrous Oxide	N_2O	310	N
Sulphur Hexafluoride	SF_6	23,900	N
Perfluorocarbons*	PFCs	Variable	N
Hydrofluorocarbons*	HFCs	Variable	N

Applicability **[Who is the intended user(s) for this protocol?]**

This protocol is intended for landfill operators and operators of methane biofiltration systems. It is also applicable to any facility where vented methane gas can potentially be captured and passed through a biofiltration system. This protocol will be of interest to operators seeking a cost effective methane abatement technology. This particularly applies to landfills in small communities and abandoned or closed landfills where the costs do not justify the implementation of a gas extraction system. The system is low cost, easy to construct and operate, easy to monitor and low maintenance.

Regulatory Requirements **[Describe all relevant regulations that apply to this activity and explain how the activity is going beyond regulatory requirements.]**

There are no regulations requiring the use of biofiltration specificaally but this project support initiatives that are already in place. The *Specified Gas Emitters Regulation* requires Alberta requires facilities that emit more than 100,000 tonnes of carbon dioxide equivalent (including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) to reduce emissions intensity. The *Specified Gas Reporting Program* requires industrial facilities that emit more than 50,000 tonnes of carbon dioxide equivalent to submit annual reports on their greenhouse gas emissions. Facilities that do not meet these threshold but who still wish to report their greenhouse gas emissions may do so under the *Specified Gas Reporting Program*. Industry trends show that these thresholds may drop eventually and that some municipalities may introduce mandates to address landfill gas even without provincial regulations. This protocol would supports voluntary programs to address greenhouse gas as well as provides a cost effective treatment for operators needing to meet their greenhouse gas reduction targets.

Additionality **[Explain how this activity result in real, quantifiable, and verifiable reductions beyond business as usual activity and government regulations. How does this protocol result in new, incremental greenhouse gas emission reductions and/or removals that would not otherwise have occurred? Additionality is considered in conjunction with sector level adoption and the barriers analysis provided below.]**

In conjunction with the above, the following must be addressed within the Additionality discussion for this project type.

- **Is the activity required by law, regulation or directive?**
- **What alternatives to the project activity?**
- **What is the sector level adoption for this activity (current as of 2010 year)?**

This biofiltration process is a controllable process and includes methods to measure, monitor and verify the results. At present, this technology has been demonstrated on a full size pilot scale. Widespread adoption could result in new and incremental greenhouse gas emissions that would not otherwise have occurred.

Projects implemented under this protocol will be additional. The use of biofilters is not required by law nor is the reduction of fugitive emissions from landfill covers. The materials used in this biofiltration application are readily available and economical. At present there are no readily available direct alternatives to the project activity for this application. The business as usual case is the continued and uncontrolled emission of methane from landfill covers or in economically favorable conditions the installation of active landfill gas collection systems. This project therefore results in direct greenhouse gas reductions over the baseline condition.

Since these projects currently do not present a return on investment without the offset program, it is driven by the desire of an operator to adopt environmental controls. The lack of financial incentives has been a significant barrier to project implementation to date. There are no regulatory requirements for operators to mitigate the volumes of methane being emitted from small sources like the ones that would be appropriate for this technology. Widespread adoption of this project therefore relies on financial incentives such as those provided by the offset program. To date the development of this project has focused on the technical barriers such as techniques to accurately measure methane oxidation in the field while evaluating the performance of the biofilter/biocap systems under different conditions.

Barriers **[Identify barriers that would, in absence of the offset protocol, disincent or prevent this activity or project from taking place. Barriers may be technical, financial, or social, and may be one large barrier or a number of small barriers that affect the ability of a project activity to move forward. Each barrier should be discussed in the context of the reduction/removal activity and will be used to support project addtionality]**

Given that this technology is relatively new for this scale of operation, the barriers to implementation have traditionally been primarily technological and financial. The development of this protocol will assist in overcoming the financial barrier, and the technical barriers have been overcome with the research work done by EBA in conjunction with Alberta innovates and the Edmonton Waste Management Center of Excellence at the Leduc and District Regional Landfill and with more recent collaboration with the University of Calgary.

The technical barriers to this project are related to the performance of biofilter/biocovers under various conditions and the ability to monitor and control this performance. During the last decade of research the variables that impact the performance have been studied and strategies and techniques developed to provide longevity and maintain performance. Climatic and seasonal changes are uncontrollable but these systems are designed to perform over a wide range of conditions. The ability to provide quality control is an important element of these projects and monitoring is an important element of project implementation.

Even though the cost of a biofiltration system is not high, the implementation of these projects is cost restrictive due to the fact that many landfills do not operate for profit and are hesitant to invest in capital projects. The cost attached to the implementation of the project includes the cost of materials and the cost of instrumentation required to monitor to an ISO 14064 standard. There would also be a minimal ongoing operating and maintenance cost.

Permanence **[Are emission reductions and/or removals reversible. If so, how does the protocol developer propose to address permanence of offset credits associated with this activity?]**

The conversion of methane to carbon dioxide is permanent and not reversible.

Leakage **[Will this protocol result in or threaten leakage of greenhouse gas emissions, and if so, how will these risks be mitigated? Include a discussion on possible scenarios that may occur.]**

There is no leakage since methane is destroyed by the process and not shifted up/downstream of the activity. The biofiltration process produces carbon dioxide which is a less potent greenhouse gas providing a net reduction in emissions due to the global warming potential of methane.

Conservativeness **[How does the proposed protocol idea address conservativeness in emission reduction quantifications?]**

This method assumes that all the carbon dioxide produced is a result of methane oxidation. However, the organic materials present in the biofilter/biocover can produce carbon dioxide from its own organic content. Also, the actual process of methane oxidation produces some cell matter by growth of bacteria. The amount of carbon not accounted for due to these factors is unknown but expected to be very low when compared to the actual carbon in the carbon dioxide produced by methane oxidation. This factor would have the most significant impact at the beginning of the biofiltration activity when growth of bacteria is rapid and increasing and the organic matter in the media may not be completely stabilized.

The accuracy of the methodology developed is dependent on a number of factors which are both technical and environmental. Measured quantities are used to determine baseline and is subject to the accuracy of the instruments involved in measurement. Calibration and maintenance of equipment needs to be regularly performed and documented. The protocol will use a safety factor which is conservatively anticipated to be in the range of 5%.

Aggregation **[Is this protocol likely to result in aggregated projects? If so, are there risks associated with aggregated projects, and how does the protocol propose to handle these risks?]**

The protocol will result in aggregated projects either on the same site or on separate sites. Multiple biofilter/biocaps can be installed on one particular site as part of an aggregated system. Also, separate biofilter units can be installed in combined systems with separate units used in parallel or in series as part of a complete system. Units can be located at different sites in Alberta in the same or different Cities, Municipalities, Counties and by different operators and aggregated to improve greenhouse gas reductions of the project.

Verification **[What types of records are available to support implementation and verification of the proposed activity or project?]**

There is more than a decade of research on methane oxidation for this application both on the science and the methods used to quantify methane oxidation. This research has been carried out in Alberta and is appropriate to the conditions in the province. Evidence of the feasibility of project implementation has been obtained from pilot studies both on a laboratory scale but more importantly from a demonstration project at the Leduc and District Regional Landfill. The project is instrumented such that methane oxidation can be recorded, proven and reported. The protocol will include methods to monitor and document the oxidation of methane that is achieved and provide quality records to support an independent third party review of the project condition and associated emissions reductions. These include methane removal calculations and methane composition profiles.

Ownership **[Identify issues around ownership chain that pertain to this activity or project.]**

Issues surrounding ownership are not anticipated. The protocol requires that documentation of all activities and can be used to establish ownership of the project. Ccontractual agreements should be made between project developers and operators prior to project implementation.

Related Protocols and/or Methodologies **[Do other jurisdictions, programs or offset systems have similar or related protocols available, and if so, discuss similarities and differences between the proposed protocol idea for Alberta relative to other jurisdictions. Please also indicate knowledge gaps and areas where more research is needed or being undertaken to further support the proposed activity]**

There are currently no other protocols for methane oxidation in other jurisdictions in Canada. Major obstacles to the development of a protocol in other jurisdictions have been the lack of technical knowledge and proven demonstration projects, and the lack of a financial instrument such as the Alberta Offset System. There is research in methane oxidation that has been carried out in other jurisdictions in Canada. As previously mentioned biocovers have been implemented in Nanaimo and Columbia-Shuswap Regional District of British Columbia and a biofilter is currently being implemented in Fernie. It is likely that there are other projects or research that have been carried out or are being carried out using different techniques. The principal operation of methane biofiltration systems are based on a common science, however there may be some differences in terms of the filter or cover media and the techniques used for measurement. Differences in the material are accounted for in the methane oxidation potential estimate and impact the performance of the media but not the calculation of the methane oxidation reduction. In other words a less effective media will produce less opportunity of greenhouse gas reduction credits.

There is a great deal of collective knowledge on methane oxidation considering the level of research in the subject not only in Canada but also in Europe where research has been taking place simultaneously and using very similar methods (Streese-Kleeberg et al., 2007) (Streese and Stegmann 2003) (Bohn and Jager 2009) (Börjesson et al., 2007) (Bergman et al., 1993).

Other Benefits **[List all associated benefits that will result from this activity. These other benefits can include environmental benefits, economic benefits, etc.]**

Environmental benefits include reductions in non-methane organic compounds (NMOCs) in landfill gas many of which are toxic, risk reduction from exposure to harmful compounds in landfill gas including methane and NMOC, odour reduction, greenhouse gas reduction, economic development for smaller and rural facilities, training for operators and promotion and support of voluntary greenhouse gas reduction.

Adverse Effects **[List any adverse effects that may result from implementing this activity or project.]**

There are no anticipated adverse effects associated with the implementation of this technology.

Proposed Timing for Submission into the Offset System Review Process **[Please identify the anticipated submission date for this protocol to be considered for stakeholder review. Note: the stakeholder review is held once per year in the fall.]**

The anticipated date for submission of this protocol into the offset system review process is fall 2011.

References [Provide a list of relevant references.]

Arulneyam, D. and T. Swaminathan (2000). Biodegradation of ethanol vapour in a biofilter, Bioprocess Engineering, 22, 63-67.

Bergman H., A. Jacobsson and A. Lagerkvist (1993). Investigations regarding biofilters for methane oxidation in landfill top covers. In: Cossu R, Christensen T and Stegmann R (Eds.): SARDINIA 1993, 4th International Landfill Symposium, Proceedings. CISA, Cagliari, 171-728.

Bohn, S. and J. Jager (2009). Microbial methane oxidation in landfill top covers. In: Cossu R, Diaz LF and Stegmann R (Eds.): SARDINIA 2009, 12th International Waste Management and Landfill Symposium, Proceedings. CISA, Cagliari.

Börjesson, G., J. Samuelsson and J. Chanton (2007). Methane oxidation in Swedish landfills quantified with the stable isotope technique in combination with an optical method for emitted methane. Environmental Science & Technology 41 (19), 6684-6690.

Chandrakanthi, M., A. Mehrotra and J.P.A. Hettiaratchi. (2005). Thermal conductivity of compost used in Methanobiofilters: An Experimental and Theoretical Investigation. Journal of Environmental Pollution, Vol. 136, pp. 167-174.

Chung Y.C., C. Huang and C.P. Tseng (2001). Biological elimination of H2S and NH3 from waste gases by biofilter packed with immobilized heterotrophic bacteria. Chemosphere, Vol. 34, pp 1043-1050.

Environment Canada. (2010). National Inventory Report 1990-2008: Greenhouse Gas Sources and Sinks in Canada.

Hurtado, O.D. (2009). Thin Biocovers for Methane Emission Mitigation. Ph.D. Thesis. University of Calgary, Canada.

IPCC Working Group I, 2001. Climate Change (2001). The Scientific Basis. Cambridge, Cambridge University Press, UK.

Perdikea, K., A. Mehrotra and J.P.A. Hettiaratchi, (2008). Study of thin biocovers (TBC) for oxidizing uncaptured methane emissions in bioreactor landfills. Journal of Waste Management, Volume 28, Issue 8, pp. 1364-1374

Perera, M.D.N. (2000). An evaluation of closed flux chamber technique for gas emission measurement from lanfills. Master Thesis. University of Calgary, Canada.

Philopoulos, A. (2006). A Lab and Field Scale Evaluation of Reducing Landfill Greenhouse Gas Emissions with a Methane Oxidizing Biofilter, Master of Science Thesis, University of Alberta.

Pokhrel, D. 2006. Compost based biocap performance. Ph.D. Thesis. University of Calgary, Canada.

Stein V.B. (2000). Methane oxidation in soils as a tool for reducing greenhouse gas emissions. Master Thesis, University of Calgary, Canada.

Stein V.B. and J.P.A. Hettiaratchi (2001). Methane oxidation in three Alberta soils: Influence of soil parameters and methane flux rate. Environmental Technology 22, 101-111.

Streese-Kleeberg, J., M. Ritzkowski and R. Stegmann (2007): Carbon credits trading with biological methane oxidation and in-situ stabilisation of landfills - premises and perspectives. In: Cossu R, Diaz LF and Stegmann R (Eds.): SARDINIA 2007, 11th International Waste Management and Landfill Symposium, Proceedings. CISA, Cagliari.

Streese, J and R. Stegmann (2003). Microbial oxidation of methane from old landfills in biofilters. Waste Management 23 (7), 573-580.

Tahraoui K. and R. Denis (1998). Biodegradation of BTX vapors in a compost medium biofilter. Compost Science and Utilization 6(2), 13-21.

Wilshusen, J.H. (2002). An investigation of the role of oxygen and nitrogen in methane oxidation and the formation of exopolymeric substances (EPS) in biofilters. Master Thesis. University of Calgary, Canada.

Wilshusen, J.H., J.P.A Hettiaratchi, and V.B. Stein. (2004). Long-term behavior of passively aerated compost methanotrophic biofilter columns. Journal of Waste Management. Volume 24, Issue 7, pp. 643-653.

Wilshusen, J.H., J.P.A Hettiaratchi, A. De Visscher, and R. Saint-Fort. (2004). Methane oxidation and formation of EPS in compost: effect of oxygen concentration, Journal of Environmental Pollution, Vol. 129, pp.305-314.

Yang, H. B., and Minuth (2002). Effects of Nitrogen and Oxygen on Biofilter Performance, Journals of the Air and Waste Management Association, 52 (3), 279-286.

Zeiss, C. (2002). Methane oxidation as an engineered greenhouse gas reduction method for solid waste landfills. GMEF 1130, The Federation of Canadian Municipalities, Ottawa, Ont.